International Journal of Geographical Information Science, 2014
Vol. 28, No. 10, 2030–2051, http://dx.doi.org/10.1080/13658816.2014.922686

Multi-perspective 3D panoramas

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(*Received 9 July 2013; accepted 6 May 2014*)

This article presents multi-perspective 3D panoramas that focus on visualizing 3D geovirtual environments (3D GeoVEs) for navigation and exploration tasks. Their key element, a *multi-perspective view* (MPV), seamlessly combines what is seen from multiple viewpoints into a single image. This approach facilitates the presentation of information for virtual 3D city and landscape models, particularly by reducing occlusions, increasing screen-space utilization, and providing additional context within a single image. We complement MPVs with cartographic visualization techniques to stylize features according to their semantics and highlight important or prioritized information. When combined, both techniques constitute the core implementation of interactive, multi-perspective *3D panoramas*. They offer a large number of effective means for visual communication of 3D spatial information, a high degree of customization with respect to cartographic design, and manifold applications in different domains. We discuss design decisions of 3D panoramas for the exploration of and navigation in 3D GeoVEs. We also discuss a preliminary user study that indicates that 3D panoramas are a promising approach for navigation systems using 3D GeoVEs.

Keywords: multi-perspective visualization; panorama; focus + context visualization; 3D geovirtual environments; cartographic design

1. Introduction

This article presents 3D panoramas for the multi-perspective, cartographic visualization of 3D geospatial models such as virtual 3D city and landscape models. This section introduces 3D geovirtual environments (3D GeoVEs) as the underlying conceptual and technical basis of 3D panoramas. Inherent limitations of the standard perspective projection used to map 3D models to a 2D canvas are discussed. Finally, we show how cartographic design guidelines can be implemented for 3D panoramas by non-photorealistic, cartographic visualization techniques.

1.1. 3D Geovirtual environments

3D GeoVEs are systems and applications based on 3D (geo)spatial models that integrate general 2D, 2.5D, and 3D geoinformation into a single frame of reference. These GeoVEs are generally constituted by virtual 3D city or landscape models. 3D GeoVEs commonly offer interactive 3D visualization to enable users to navigate through, explore the contents of, and interact with the underlying geoinformation space and its contents in various applications. These include navigation systems, urban planning and development,

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infrastructure management and maintenance, environmental simulation, and risk and disaster management.

3D GeoVEs provide key advantages for the interactive communication of geoinformation, including interactive information access, an adaptive degree of information intensity, the intelligent behavior of model components, and the immersion of the user into 3D representations (MacEachren *et al*. 1999). Compared to maps, the shape and appearance of features is not symbolized but can be preserved. Thus, a user does not necessarily require the knowledge of a semiotic model to decode the visualization. To this end, 3D GeoVEs enable the implementation of geovisualization approaches based on 'naive geography' and 'neocartography' (Egenhofer and Mark 1995, Cartwright 2012).

Rapid advancements in methods and technology for the acquisition and provision of 3D spatial models, especially virtual 3D city models, have resulted in a variety of popular applications that depict virtual reality in a realistic way, such as Google Earth™ and Nokia Maps 3D™. These applications are to a large extent driven through advancements in 3D computer graphics (such as graphics processing units (GPUs), level of detail (LoD) rendering algorithms, and shader technology), for example, using virtual globes to enable a general purpose exploration of 3D geodata, but less through progress in visualization techniques (Bleisch 2012). For example, interactivity and adaptive information density should be taken into account for a user-dependent, context-dependent, and media-dependent visualization for 3D GeoVEs.

1.2. Problem statement

Geovisualization systems and applications commonly apply the standard perspective projection to map 3D models onto a 2D canvas. In computer graphics, standard camera models are based on perspective or orthogonal projections. These have long been mandatory in the fixed-function rendering pipeline, because only these types of projections have been supported by graphics hardware and could achieve interactive performance. In the following, these camera models are referred to as *perspective views*. According to Jobst and Döllner (2008b), perspective views result in the following key limitations to communication of 3D geodata by means of 3D visualization (Figure 1a):

- **Occlusion.** Compared to close objects, distant objects typically are not visible or are only partially visible due to occlusion.
- **Partial use of screen space.** In low view angles (e.g., on a pedestrian level), a large amount of screen space is often visually cluttered (e.g., areas far away from the virtual camera) or is used for displaying the horizon, and thus, it is not actively used for information representation.
- **Absence of map scales.** A key component of 2D maps is a uniform scale, which enables a user to measure, estimate, and compare spatial relations. Because of perspective distortion, the spatial 3D model cannot be drawn to a fixed scale. The variation of scales complicates the estimation and comparison of spatial relationships.

To explore occluded parts of a 3D GeoVE, the perspective view can be changed by modifying the virtual camera using interaction and navigation techniques. The 3D interaction techniques provided by user interfaces, however, lead to additional cognitive load and can affect a user's performance, for example, on comparison tasks (Plumlee and Ware 2006). Because of the limited capacity of a human's working memory for visual attributes such as colors, textures, and structures of geometry objects (Brady *et al*. 2011), the

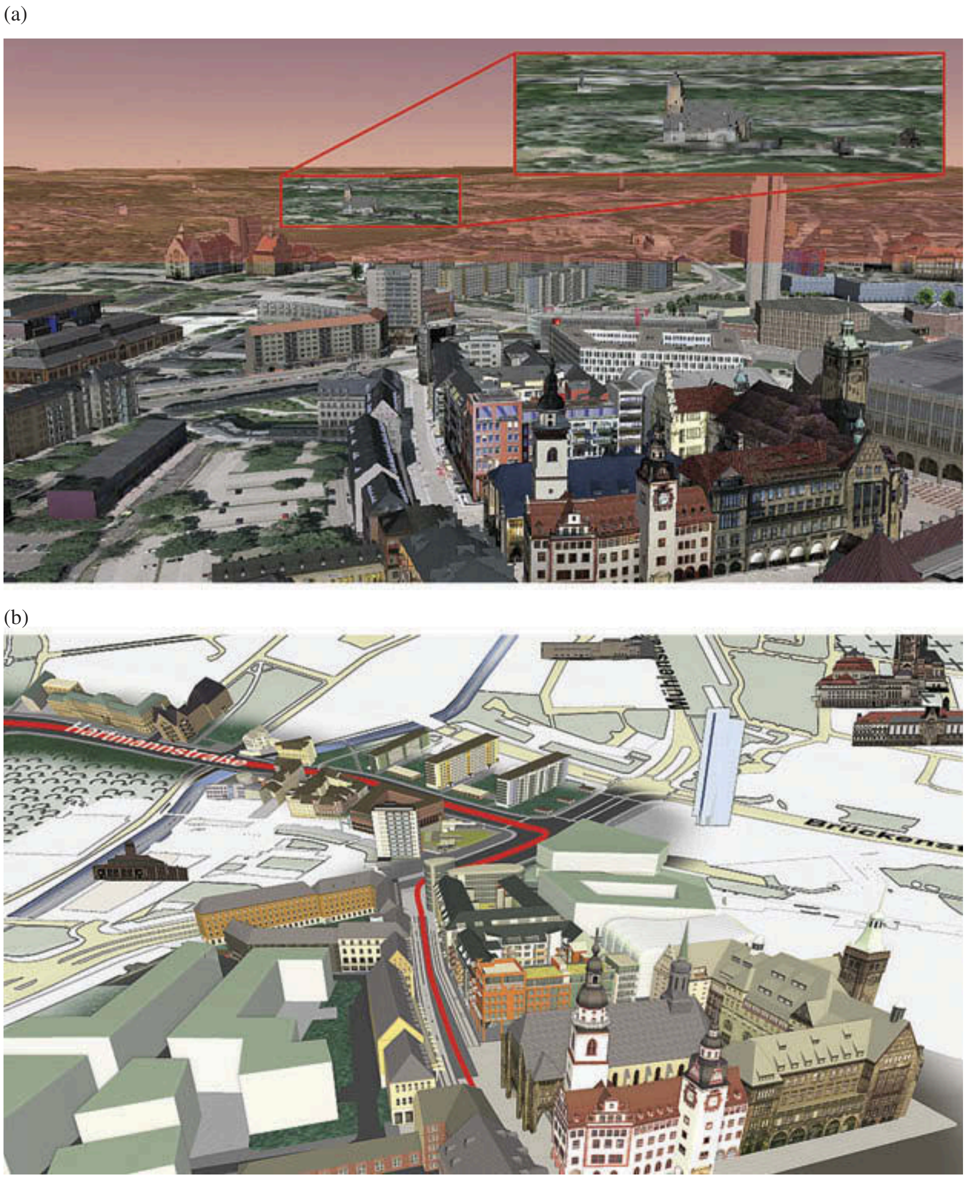

Figure 1. (a) Standard 3D visualization of a virtual 3D city model in Google Earth™. Because of the perspective view, the background (red overlay) contains a horizon and visual clutter, reducing information entropy. (b) The degressive 3D panorama bends the 3D GeoVE toward the user, thus, replacing the horizon and reducing visual noise. A cartographic visualization is used to highlight task-relevant information.

process of mentally relating different views to each other is demanding and error-prone. Here, visual information with high details leads to a fourth key limitation:

- **Visual clutter.** Because of perspective distortion, the size of more distant objects on-screen decreases. As a result, distant objects are more and more difficult to identify as they are mapped to increasingly fewer pixels. The detailed or realistic depiction of objects particularly leads to 'visual noise' (cf. inset Figure 1a).
  A key concept and technique to tackle this issue is adaptive *level-of-abstraction* (LoA) visualization. LoA refers to the spatial and thematic granularity with which model content is represented; it extends concepts of geometric simplification, for

example, LoD, by visual abstraction and generalization. It is similar to the *iconicity* concept presented by MacEachren *et al*. (1999):

- **Low LoA:** A visualization with a low LoA (i.e., an iconic visualization) may include many details facilitating the mental mapping of 3D virtual objects to real world objects, but it may not include task-specific information.
- **High LoA:** A visualization with a high LoA (i.e., an abstracted visualization) may include only a few important or prioritized details facilitating the identification of coarse structures, such as street networks, and the generation of a mental map (Mania *et al*. 2010, Stinson *et al*. 2011).

Geoinformation is neither categorized nor prioritized in an iconic visualization with a uniform LoA, which further complicates the perception of task-relevant or prioritized geoinformation.

Cockburn *et al*. (2009) reviews a variety of interactive visualization approaches that cope with the uniform LoA in 3D GeoVEs, for instance, zooming user interfaces, detail + overview, and focus + context visualization. Nevertheless, the limitations and challenges of the underlying perspective views remain.

1.3. 3D Panoramas

Multi-perspective 3D panoramas (Figure 1b) combine design aspects from cartography with rendering techniques from computer graphics and concepts of information visualization. The overall goal of our visualization techniques is to cope with the above limitations of the common visualization of 3D GeoVEs and, in particular, to support users in navigation and exploration tasks.

Our 3D panoramas are based on the multi-perspective visualization technique presented in Pasewaldt *et al*. (2011). A key principle of *multi-perspective views* (MPVs) is to seamlessly combine multiple views, taken from different viewpoints, into a single image (Vallance and Calder 2001). Using more than one viewpoint, MPVs can reduce occlusion, increase screen-space usage, and reduce perspective distortion as well as visual clutter. Further, MPVs enable the definition of use-case-specific projections, for example, for navigation tasks. According to Elvins (1997), navigation in unknown spaces and the generation of a mental map requires the acquisition of (1) landmark knowledge, (2) procedural knowledge, and (3) survey knowledge. Landmarks are prominent objects in the (virtual) environment that are defined according to singularity, prominence, meaning, and category. Visual singularity in particular, that is, the visual distinction of a landmark from its surroundings, can be communicated with 3D GeoVEs by using an upright projection and a low LoA. Procedural knowledge is gained by navigating a route and determining turns and the distances between those turns. This can hardly be achieved with perspective views because of the perspective distortion and, thus, the absence of map scales. Hence, a 2D map would be a more appropriate tool.

We propose a *degressive 3D panorama* for navigation tasks, which bends the 3D virtual world toward the viewer, separating the view into (1) a focus zone using a low view angle, (2) a context zone using a steep view angle, and (3) a transition zone that degressively interpolates the view angle between (Figure 2). The focus zone remains unchanged with respect to the perspective view, offering a detailed 3D view for the local neighborhood and landmarks, while the horizon in the context zone is replaced by an orthographic view, thus increasing screen-space utilization, reducing occlusion, and incorporating more context information (e.g., route turns) (Figure 1b). The perspective

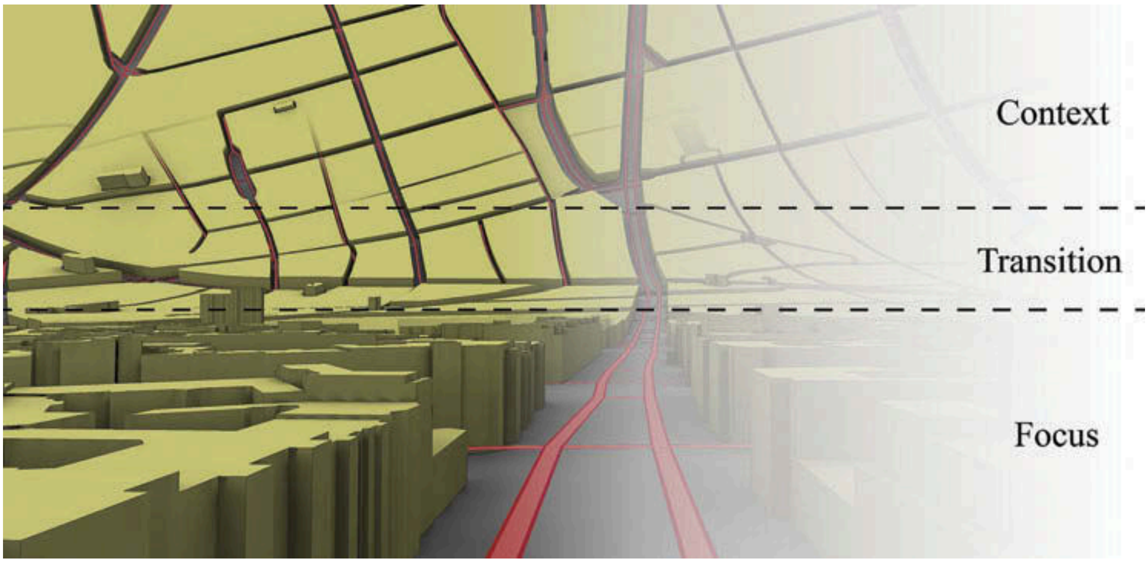

Figure 2. Conceptual sketch of the MPV subdivision into (a) a focus zone in the foreground, (b) a context zone in the background, and (c) a transition zone between. The two principle perspectives of the focus and context zone are seamlessly interpolated in the transition zone.

distortion is reduced in the context zone, supporting the estimation of distances. In this way, more information can be encoded into the available screen space. By presenting task-relevant information, the interaction between the user and virtual camera control can be reduced, and the task performance of a user can be increased (Keehner *et al*. 2008).

To reduce visual complexity and visual clutter while highlighting task-relevant information, the panoramas can be further enhanced by applying cartographic visualization techniques. *Cartographic visualization* refers to methods and techniques that incorporate principles of classical cartographic presentations in rendering techniques used by visualization systems and applications (Semmo *et al*. 2012). With the advance of real-time rendering technology, the implementation of these techniques becomes possible as part of the real-time rendering pipeline. A cartographic visualization is essential to provide different LoAs, ranging from near photorealistic, iconic depictions to completely abstracted, symbolic depictions of map contents or of 3D GeoVEs. Further, the different LoAs, which are generated by cartographic visualization techniques, enable us to optimize perceptional, cognitive, and graphical design issues by emphasizing relevant or prioritized information and by omitting less relevant information in order to direct a user's focus-of-attention (DeCarlo and Santella 2002, Santella and DeCarlo 2004, Cole *et al*. 2006).

The remainder of this article is structured as follows. Section 2 summarizes related work on cartographic generalization and visualization, focus + context visualization, computer-generated panorama maps, and non-photorealistic rendering (NPR). Section 3 outlines technical and conceptual details of 3D panoramas as well as cartographic visualization. Results are discussed in Section 4. Finally, Section 5 concludes the article.

2. Related work

Our work is related to several previous studies in the domains of cartographic generalization and visualization, focus + context visualization, computer-generated panorama maps, and NPR.

2.1. Cartographic generalization and visualization

2D (digital) maps are commonly used for navigation and exploration tasks. The aim of a map is to successfully communicate geoinformation between a cartographer (the map producer) and a user (the map consumer). Geodata is encoded using a semiotic model and is transferred by the map. For a successful communication, the map consumer must understand the semiotic model to decode the information. Further, a map should satisfy the needs of the map consumer in order to improve the communication process; the map should be readable, comprehensible, and visualized in such a way that the information can be memorized easily and so that emotional aspects are addressed in addition to rational aspects (Koláčný 1969).

According to Brodersen (2007), the geocommunication process is successful if the map producer and the map consumer 'agree' on aspects of location or space. In the context of the presented 3D panoramas, this agreement is facilitated by adapting the following cartographic design guidelines:

(1) **Decrease of visual complexity by classification, symbolization, and abstraction.** Häberling *et al*. (2008) define the following three design steps for digital 3D maps: (1) modeling, (2) symbolization, and (3) visualization. For each design step, the map producer can choose between different design aspects to configure the map to fit a user's needs and to ease the communication process. For example, the visual complexity of objects within 3D GeoVEs can be lowered by modifying their geometric representation (modeling), abstracting their visual appearance (symbolization), or simplifying the shading (rendering).

(2) **Decrease of occlusion and visual clutter.** Although Häberling *et al*. (2008) proposed design variables for parameterizing the projection of the virtual camera (e.g., orthographic and cylindrical projection), the perspective projection is most often applied for 3D GeoVEs. To reduce occlusion, Häberling *et al*. (2008) suggest a viewing inclination of 45° and generalization to minimize visual clutter. An alternative approach is used in panoramic maps, where landscape artists combine multiple perspectives in a single image and distort (e.g., enlarge) map features (Patterson 2000).

(3) **Increase of user involvement.** The map design process can be described as a feedback loop between the map producer and the map consumer, where the producer designs the map according to the consumers feedback and requirements (Peterson 2005). Reichenbacher (2007a) demands 'the ability of flexible systems to be changed by a user or the system in order to meet specific requirements.' An optimal map should 'present as much information as needed (by a user) and as little as required' (Reichenbacher 2007b).

Previous work in cartography and geovisualization discusses a large repertoire of methods, techniques, and guidelines that aim to increase the effectiveness and expressiveness of 3D GeoVEs (e.g., Dykes *et al*. (1999), Jobst and Döllner (2008a)). Because of the high degree of freedom in the design and visualization of 3D GeoVEs, the modeling, symbolization, and rendering stages require generalized models to filter and outline information relevant to a user's task and context (MacEachren 1995). Here, cartographic generalization constitutes a general category of abstraction techniques, built by a set of model transformations (generalization operators) that transform geospatial data into human-readable maps (McMaster and Shea 1992). However, these techniques only partially address generalization requirements for 3D geovisualization; degree of abstraction ranging from iconic to symbolic representations (Kraak 1989, Dykes *et al*. 1999, MacEachren *et al*. 1999), the depth perception (Pfautz 2000), and the perspective distortion (Pegg 2012) are not addressed.

Generalization approaches for 3D GeoVEs have been proposed in previous works; these include techniques for 3D building models (Thiemann and Sester 2006, Kada 2007, Glander *et al*. 2009) and 2D road networks (Agrawala and Stolte 2001, Mustafa *et al*. 2001). Most of these techniques enable a dynamic and view-dependent simplification to yield different LoD representations of 3D geospatial models. Our work does not rely on specific generalization techniques but explores a combination of different LoD and LoA approaches for various feature classes. Following the approach presented by Semmo *et al*. (2012), a visualization is adjusted to a user's context and task by selecting and seamlessly combining multiple LoAs according to important or prioritized information, thus directing the gaze by salient stimuli attraction (saliency-guided visualization). Combined with MPVs, this approach is further used to reduce occlusion and visual clutter in areas located far away from the virtual camera (Jobst and Döllner 2008b), for instance by using a view-distance-based transition of LoAs.

2.2. Focus + context visualization

The expression 'focus + context' describes the concept of visually distinguishing relevant information (the focus) from nearby related objects (the context). Focus + context visualization ensures that users are aware of their position and orientation in the virtual space (Glueck and Khan 2011) and helps to avoid 'getting lost situations' (Buchholz *et al*. 2005).

A common focus + context technique for 3D GeoVEs is to use multiple generalized representations of 3D objects (e.g., LoAs) combined in a single image. A context-aware LoA has the potential to improve the perception of important or prioritized information (Santella and DeCarlo 2004) and direct a viewer's focus to certain locations within an image (Cole *et al*. 2006). Applications of focus + context visualization for virtual 3D environments include generalization lenses (Trapp *et al*. 2008), cell-based geometric generalization (Glander *et al*. 2009), panorama maps (Möser *et al*. 2008, Lorenz and Döllner 2010, Pasewaldt *et al*. 2011), focus + context zooming (Qu *et al*. 2009), and LoA transitions (Semmo *et al*. 2012) to highlight regions of interest and landmarks.

In this article, we present concepts and techniques to combine 3D panoramas with LoA transitions to enable a seamless combination of cartographic and photorealistic graphic styles while (1) minimizing occlusion of 3D geospatial objects, (2) increasing screen-space utilization, and (3) directing a viewer's gaze to important or prioritized information.

2.3. Computer-generated panorama maps and non-photorealistic rendering

Seamlessly combining multiple perspective views into a single canvas is a technique that has been applied by landscape artists for more than 400 years. A prominent example for alpine regions is the panorama map of H.C. Berann, which combined an orthographic projection for the map-like foreground with an upright projection for the detailed background. Contrary to the real world, visual landmarks (lakes and mountain peaks) are rearranged so they are disoccluded and their visibility is increased. The view in the foreground eases localization by using a map-like presentation, while the mountainous skyline eases the estimation of walking directions.

Patterson (2000) discusses design aspects and variables of Berann's panorama maps that are partially implemented by diverse multi-perspective visualization techniques (Jenny 2006, Takahashi *et al*. 2006, Falk *et al*. 2007, Degener and Klein 2009, Jenny *et al*. 2011). Most relevant work to 3D panoramas are the concepts of degressive and progressive MPVs for virtual 3D city models, presented by Lorenz *et al*. (2008) and Möser *et al*. (2008). Both works visualize a virtual 3D city model from two major perspectives, one in the foreground and one in the background, between which the perspectives are seamlessly interpolated. Lorenz *et al*. and Möser *et al*. also introduced the first concept of a view-distance-based LoA using iconic depictions in the foreground to enhance immersion and ease the mapping between the virtual and real environments and an abstracted, symbolic presentation in the background to emphasize road networks as orientation guides. This kind of focus + context visualization may be used to improve navigation and orientation tasks, for example, in pedestrian (Veas *et al*. 2012) and car navigation systems (Kim and Dey 2009), with augmented reality. The work by Möser *et al*. (2008) uses an additional adaptive isometric perspective to improve the visibility of building facades along a predefined navigation route.

Researchers agree that 3D GeoVEs should account for application space, level of interactivity, and the audience of purpose (MacEachren *et al*. 1994, Dykes *et al*. 1999, Bleisch 2012). Context-aware rendering techniques can significantly improve the perception of important or prioritized information communicated by panorama maps. For instance, NPR techniques can be used and parameterized to reduce visual complexity and direct a viewer's gaze to certain image regions (Santella and DeCarlo 2004, Cole *et al*. 2006, Semmo *et al*. 2012, Kyprianidis *et al*. 2013). An efficient communication of 3D GeoVEs, however, requires an adequate cartographic visualization and rendering techniques at the feature level (Jobst and Döllner 2008a). Cartographic rendering techniques have been subject to primary geospatial features such as terrain (Buchin *et al*. 2004, Bratkova *et al*. 2009), water (Semmo *et al*. 2013), trees (Deussen and Strothotte 2000), buildings (Döllner and Walther 2003), and landscape (Coconu *et al*. 2006) and city models (Jobst and Döllner 2008b).

We complement these techniques by our work on 3D panoramas to reduce occlusion and visual clutter in regular 3D perspective views and extend the aforementioned approaches on panorama maps by combining the cartographic visualization of Semmo *et al*. (2012) with the view-dependent MPVs of Pasewaldt *et al*. (2011). This approach enables a higher artistic control over the parameterization of resulting panorama maps, supporting the implementation of design principles from cartography. Moreover, we exemplify how an adequate cartographic visualization of geospatial relationships can be achieved by parameterizing and combining NPR techniques within a single view according to semantic information. CityGML (Kolbe 2009) introduced a semantics-driven classification and exchange format that has been standardized by the Open Geospatial Consortium (OGC) and which is supported by a growing number of geographic information system (GIS) software vendors. In our system, semantic information is explicitly taken from the CityGML model or implicitly derived from material and texture information. The semantic information can be used for a task- and context-specific setup, combination, and customization of cartographic visualization techniques.

3. 3D Panoramas

Our processing pipeline for 3D panoramas is illustrated in Figure 3. The input data consists of 3D GeoVEs, commonly represented by collections of 3D models of terrain, buildings, infrastructure, vegetation, water, and land use. 3D GeoVEs can be constructed by CityGML encoded models (Kolbe 2009); CityGML provides the classification and structures for virtual 3D city and landscape models, including their geometric, topological, and semantic-related aspects as well as a LoD concept that distinguishes from LoD-1 (lowest model and semantic resolutions) to LoD-4 (highest model and semantic resolutions). In addition, 3D GeoVE components can be encoded by several 3D scene representation formats from computer graphics (e.g., X3D, 3DS), while 2D image formats (e.g., aerial photography, compressed textures) can be used to define the visual appearance. For our visualization techniques, the input data is transformed to a 3D scene graph representation of OpenSceneGraph to obtain an efficient data representation for real-time rendering purposes. The input data is classified into a set of main feature types (i.e., building, green space, street, water, or terrain) and sub-types (e.g., coniferous forest or deciduous forest).
Our visualization techniques encompass two major functional components:

- *3D Panorama Visualization* (Section 3.1): This visualization technique (Figure 3b) bends a 3D GeoVE (in terms of global deformation), depending on the camera distance, in a progressive or degressive way (Figure 4). The bending leads to a visual representation that helps reduce occlusion and visual clutter of distant 3D scene parts and enables a seamless combination of 3D and 2D depictions in a single image (Lorenz *et al*. 2008, Möser *et al*. 2008, Jobst and Döllner 2008a, Pasewaldt *et al*. 2011).
- *Cartographic Visualization* (Section 3.4): NPR techniques are used for visual abstraction according to cartographic design principles (Section 2.1) such as waterlining, signatures for green spaces, and generalization of building models (Figure 3c). Task-relevant or prioritized information is highlighted, and less relevant information is filtered by utilizing view metrics (e.g., view distance, view angle, or region interest) for a view-dependent LoA interpolation and to perform a saliency-guided visualization (Semmo *et al*. 2012).

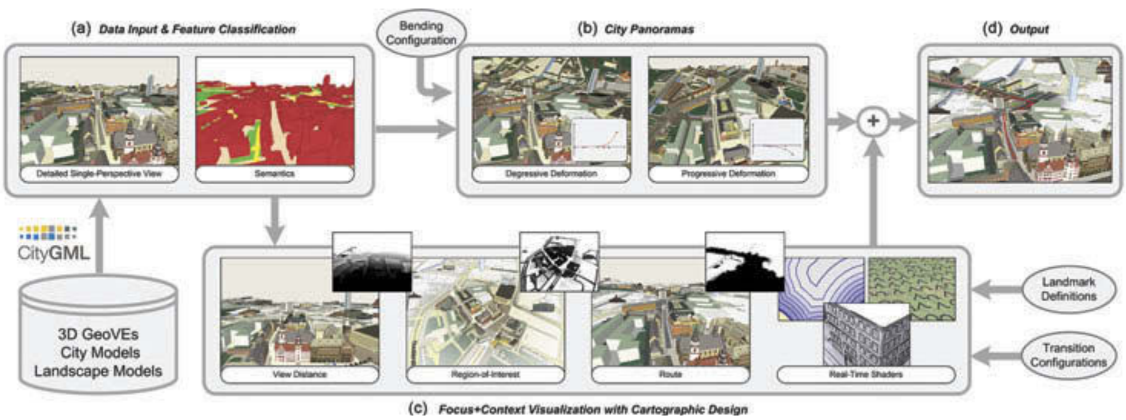

Figure 3. Processing pipeline for 3D panoramas: (a) 3D virtual city and landscape models as input and feature classification, (b) 3D panorama generation, (c) cartographic visualization based on relevance values, and (d) exemplary output that combines (b) and (c). The stages (b) and (c) can be configured to adjust the visualization to a user's task and preferences.

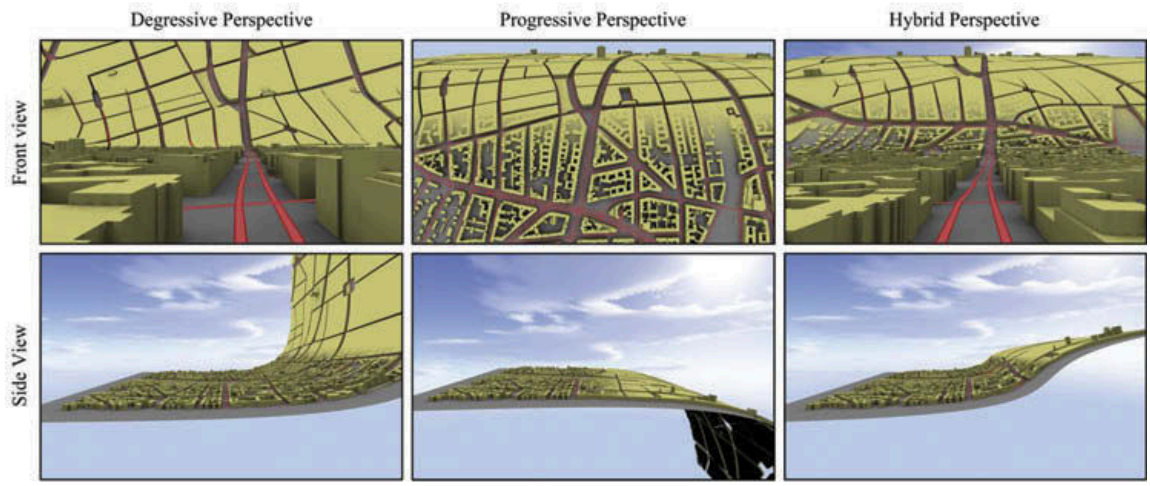

Figure 4. Front and side view of common 3D panorama configurations. The flexibility of a parametric curve, used to control the panorama shape, enables numerous different configurations. The degressive perspective (DP) helps to answer the question, 'Where am I going to?' by displaying context along the driving or walking direction. The progressive perspective (PP) helps to answer the question, 'Where am I, and which direction am I looking?' by depicting 3D views on landmarks.

Both visualization techniques are technically and conceptually orthogonal to each other. For that reason, they can be combined or deployed as stand-alone techniques. They can also be integrated into existing visualization systems.

3.1. 3D Panorama configuration

To specify a 3D panorama, a set $\mathcal{P}_\phi = \{P_{\phi_0}, P_{\phi_1}, \ldots, P_{\phi_n}\}$ of presettings P_{ϕ_i} must be defined. P_{ϕ_i} is defined as vector $P_{\phi_i} = (C(t), s, e, \phi_i)$ with $C(t)$ being a B-Spline curve used to control the shape of the panorama, for example, a progressive, degressive, or hybrid perspective (Figure 4). The scalars s and e define the start and end points of the 3D panorama with reference to a viewer's position (Figure 5). Each presetting is associated with a viewing angle $\phi_i \in \left[0.0, \frac{\pi}{2.0}\right]$. Based on the current viewing angle α, a function *interpolate* $\left(\mathcal{P}_\phi, \alpha\right)$ yields a 3D panorama configuration by linearly interpolating $C(t)$, s, and e of two presettings P_{ϕ_i} and P_{ϕ_i+1} with $\phi_i \leq \phi_{i+1}$.

Although the parameterization of $C(t)$ yields an arbitrary number of panorama configurations, cartographers primarily focus on degressive or PPs (Jobst and Döllner 2008b). Both perspectives are suitable for a focus + context visualization, as they subdivide the panorama into two *principal perspectives* of the foreground and background regions, similar to the hand-drawn landscape panorama maps of Berann. The view-dependent interpolation enables a designer to combine multiple panorama configurations into one visualization. For example, a DP for a low viewing angle can be combined with a PP for a steep viewing angle. During user interaction, the perspectives are adjusted automatically.

3.2. 3D Panorama bending implementation

Global deformations are used for implementing bending operations, that is, the geometric representation of all components of the 3D GeoVE are modified per frame during image synthesis. A global deformation matrix is computed for each vertex; to ensure real-time

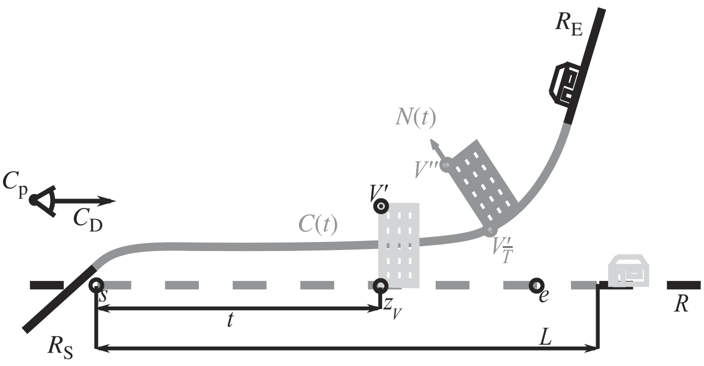

Figure 5. Schematic overview of the global deformation process for the 3D panorama generation. During image synthesis, every vertex V' is transformed in the vertex shader to its final position (V'') on the B-Spline curve.

rendering, the main workload is shifted to the GPU. In the following, we outline our GPU-based implementation using OpenGL vertex shaders for global deformation.

The bending technique assumes that a reference plane R (Figure 5) is predefined for a given 3D GeoVE; every vertex $V' = (x, y, z) \in \mathbf{R}^3$ is projected onto that plane. The B-Spline curve $C(t)$ is computed on the CPU and then is arc-length reparameterized (based on L) and passed to a vertex shader using a 1D RGBA texture. Afterward, the normalized distance $t = \frac{z_v - s}{e - s}$ of V' from the camera's position (C_P) along the camera's viewing direction C_D between s and e is computed on the GPU. t is used to evaluate the B-Spline curve $C(t)$ to compute a deformed vertex V'_T. V'_T is then translated along the normal $N(t)$ of the parametric curve by its original height above R to yield the deformed vertex V''. Vertices that are not between s and e, that is, $z_{V'} < s$ or $z_{V'} > e$, are mapped to a start or end reference plane (R_S and R_E).

The 3D panorama visualization technique can be combined with existing real-time 3D rendering techniques, because the global deformation can be fully separated and encapsulated by a corresponding vertex shader program. This enables systems and applications to use the bending together with common 3D rendering techniques, as provided by 3D middleware systems or with specialized techniques (e.g., illustrative rendering).

3.3. *Levels-of-abstraction implementation*

3D panoramas take advantage of the ability to combine different LoAs with respect to the geometric representation in order to improve visual clarity and unambiguity as well as to stress the synthetic nature of the displayed scenery. For instance, the hybrid perspective in Figure 4 could be interpreted as hilly landscape. To prevent such confusion, different LoAs of the 3D GeoVE are used for the principal perspectives.

For this, the presetting P_{ϕ_i} is extended by a stylization description set $\mathcal{S} = \{S_0, S_1, \ldots, S_l\}$, which defines a different number of stylization zones $S_i = (T_i, T_{i+1}G_j)$. $T_i = (t, \delta)$ is a *tag point* that defines the beginning (t_{T_i}) and end ($t_{T_i} + 1$) of a stylization zone as well as a neighborhood δ around t_i, where consecutive zones are blended. $G_j \in \mathcal{G}$ is an (abstracted) geometric representation of the 3D GeoVE, with $\mathcal{G} = \{G_0, G_1, \ldots, G_m\}$ being a list of multiple LoAs (e.g., three to five different geometric representations).

In Figure 4, three LoAs have been used, one representing the original city model and two variants generalizing the city model according to two different granularity levels of the street network, resulting in building block cells (Glander *et al.* 2009). In particular, LoAs can treat landmarks in a special way to ensure their existence and visibility in the final panorama (Glander *et al*. 2007). This is especially important for the background regions of the 3D panorama, because it can reduce visual clutter and emphasize relevant information such as road networks and landmarks.

To combine the different LoAs in the final image, each LoA is deformed using the same B-Spline configuration $C(t)$ and is written to a separate texture using offscreen rendering. In a final compositing step, the multiple images are blended with a corresponding OpenGL fragment shader.

3.4. Cartographic visualization techniques

The 3D panorama visualization technique is combined with the visualization framework of Semmo *et al*. (2012) to highlight task-relevant information and clarify the visualization by reducing visual complexity and clutter. The framework is used to define and interpolate between multiple LoAs for different entity types such as buildings, street networks, and vegetation. The design of the different visualization and rendering techniques used to generate the LoAs is inspired by the semiotics of 2D topographic maps and incorporates the three design stages of Häberling *et al*. (2008) (Section 2.1).

Our cartographic visualization techniques can be defined and parameterized in two principal ways:

- According to the model semantics such as feature type information (i.e., building, green space, street network, water, or terrain) (Figure 6).
- According to 'relevance values' that are either explicitly defined (e.g., region interest, route) or implicitly computed by view metrics (e.g., view distance, view angle) to enable a dynamic, context-dependent visualization.

Semantics of 3D GeoVE for Parameterization. The semantics provided by 3D GeoVE (e.g., encoded by CityGML) are used to set up and adapt the parameters of cartographic visualization techniques. The following examples illustrate how to apply different rendering techniques based on entity type information for a cartographic visualization of 3D GeoVEs (Figure 6):

Street networks are stylized using cartographic color schemes (Brewer 1994) and the image-space edge enhancement technique by Nienhaus and Döllner (2003) to emphasize contour lines and help a user distinguish street networks from the embedding context. Further, street labels are rendered using alpha-tested distance maps (Green 2007) and are scaled and aligned view-dependently (i.e., to face the major view direction).

Figure 6. Examples of cartographic visualization techniques for (a) building facades, (b) street networks, (c) water surfaces, (d) green spaces, and (e) digital terrain models.

Water surfaces are visualized using the algorithms presented by Semmo *et al*. (2013). Texture features (i.e., water stipples, hatches, waterlines) are aligned to shorelines to improve figure-ground perception and to express a sense of motion, similar to classical cartographic depictions of water on maps.

Green spaces are symbolized by signatures using a variant of Glanville's texture bombing algorithm (2004), which always aligns the signatures with the view direction. They are scaled according to the view distance to reduce visual clutter at high view distances. The symbols can be parameterized to reflect land-use information (e.g., arable land, grassland) and tree species (e.g., coniferous forest, deciduous forest).

Digital terrain models are visualized according to design principles of cartographic relief presentations. Loose lines, slope lines, and shadowed hachures are used to communicate geomorphologic characteristics (e.g., direction of slope). Our algorithm is based on the work of Buchin *et al*. (2004). The stroke width is varied according to the morphometric variables to express slope steepness, trenches, or crests.

Landmark information is used to perform animated transitions between a landmark's 3D representation and its 2D imposter viewed from the landmark's best-view direction (Vázquez *et al*. 2001). This way, sites that have a prominent appearance or are familiar to a user can serve as orientation guides, similar to the concept of tourist maps (Grabler *et al*. 2008).

Relevance Values. Generally, a 3D GeoVE contains both more and less relevant information for a given task. For example, during navigation in virtual 3D city models, the information in the immediate surroundings of a user or along the driving route can be more relevant because they are used to support time-critical decisions, such as which road to take at a crossing. We use simple heuristics to compute relevance values for all 3D GeoVE objects at image-synthesis time, using saliency metrics (such as view distance, view angle, or region interest). Cartographic visualization techniques use these values to select different LoAs. For example, an iconic depiction (e.g., diffuse textures) can be used for objects of high relevance, while abstract, symbolic rendering is applied for objects of low relevance.

Relevance values in between yield a mix of LoAs. Instead of using stylization zones S_i for a 3D panorama, a set of stylization descriptions $S_i^{'} = \left(u_0, u_1, u_2, u_3, G_j^{'}\right)$ is used to define and parameterize the visual appearance $G_j^{'}$ per feature type in such a way that a smooth transition is achieved during the viewer's interaction with the system. Here, $G_j^{'}$ does not just refer to a certain geometric representation, but it may also refer to an NPR effect – including its parameterization – for an LoA. The ordered parameters $u_i \in [0, 1]$ with $u_i \leq u_{i+1}$ define when and how an LoA should be applied. A transition between graphic styles is implemented on the GPU using image-based blending with linear or smooth blend functions. For instance, a blending according to the *view distance* can be defined to achieve a smooth transition between iconic graphic styles in the foreground and symbolic graphic styles in the background of a degressive 3D panorama (Figure 7). Alternatively, the *view angle* may be used as a metric for a map-like depiction of areas with a bird's eye view (e.g., the context zone) and a detailed representation for areas with a pedestrian view (e.g., the focus zone). If a user explicitly defines *regions of interest* for a given task or context (e.g., a route for navigation or an historic city center that should be explored), these regions are depicted with high detail and are seamlessly embedded within the map-like context. This way, the 3D panorama provides an overview in context areas while assisting the viewer with detailed information in the focused area.

Figure 7. Exemplary combination of a 3D panorama with cartographic visualization techniques. The example illustrates a view-distance-based transition (a) between iconic graphic styles in the foreground and symbolic graphic styles in the background. Relevance values computed for a circular region of interest and route are shown in (b) and (c).

3.5. Interaction techniques

Conventional interaction techniques (e.g., orbit, flyer, or game navigation) often rely on ray casting to determine intersections of the mouse cursor with geometric representations of the 3D GeoVE (Buchholz *et al.* 2005). For visualization techniques that modify the geometric representation during image synthesis (e.g., the 3D panorama), this approach is not applicable, since the ray cast is performed against the original geometry instead of against the deformed and 'volatile' geometry. We implemented an alternative approach using image-based navigation techniques. This approach uses a G-Buffer representation (Saito and Takahashi 1990) of the current model, including position, normal, and object-specific information (e.g., a unique identifier). Instead of casting a ray into the scene, the G-Buffer is directly sampled to determine the intersection point in 3D.

Further, we adapted the multi-scale interaction technique of McCrae *et al*. (2009) to enable an assisted, convenient navigation. This approach uses an omnidirectional depth-buffer cube-map representation of the 3D GeoVE for distance computations, to avoid collisions and adjust movement speed. The depth-buffer generation is adapted by applying the global deformation as described in Section 3.1. For point-and-click interaction and selection, the G-Buffer configuration of the 3D panorama rendering techniques has been extended to include position and semantic information, which are passed to the multi-scale navigation technique.

4. Results and Discussion

We have implemented the presented panorama visualization techniques as a real-time 3D rendering library, intended for generic integration into all kinds of 3D GeoVE applications and systems (e.g., GIS, mobile, and desktop applications). In the following, we briefly outline potential applications and discuss the techniques' benefits as well as their limitations in the context of navigation and orientation.

4.1. Application examples

Promising applications are found in mobile and augmented reality navigation systems and city maps. Veas *et al.* (2012) proposed a 'variable perspective view' for augmented outdoor navigation conceptually similar to our 3D panorama technique. They evaluated their approach using an explorative and comparative study. Although a user stated that 'seeing the horizon improved the navigation experience while observing a large area,' the performance on pedestrian navigation tasks was significantly slower compared to a 2D digital map. Further, a trend has been identified in which users prefer the panorama over the map, because it facilitates the integration of virtual objects into the real world and thus facilitates mental mapping.

Kim and Dey (2009) presented a map-like visualization for car navigation systems that projects the multi-perspective map into the car's windshield. Their evaluation focuses on navigation performance for elders and young people. The results reveal that 3D panoramas reduce context switches and produce less distraction, reducing a user's cognitive load. Hence, the participants could perform navigation tasks more efficiently with reduced task completion times and error rates.

Together with the Nokia Gate5 GmbH in Berlin, we have implemented a prototype of our 3D panorama techniques with an adaptive landmark scaling (Glander *et al*. 2007) for mobile devices. We conducted a quantitative and qualitative user study. The aim of the user test was to evaluate the acceptance, general preference, and comprehension of MPVs in a navigation scenario. To this end, side-by-side images using four different perspectives were evaluated, accompanied by the question, 'What type of visualization does a user favor to navigate along a route?' Figure 8 shows the respective perspectives: an orthographic top-down view (2D) known from common navigation systems, a 3D view with an oblique perspective (3D), a DP that shows the top-down view in the lower part of screen while the upper part shows the silhouette of a virtual 3D city model, and a PP that shows a 3D oblique view in the lower part of the screen while the upper part shows a top-down view.

Three different route categories of varying complexity were used for the test scenarios, the first being *simple routes* of short length that mostly consist of one straight segment (Figure 9a). The courses of these routes are supposed to be easily predicted, even if segments are occluded. The second were *moderately complex routes* of an increased length and more turns compared to simple routes (Figure 9b), and the third were *complex routes* that include a high number of turns and self-intersections, for example, at a motorway junction (Figure 9c). These different categories were supposed to affect the capability of a user to overview the course of highlighted routes.

During the evaluation, participants were asked to choose their preferred visualization. The hypothesis that participants would prefer MPVs over classical 2D or 3D views is based on the following rationale: compared to visualization of 3D GeoVEs using a central perspective, MPVs (e.g., a PP or DP) use available screen space more efficiently, reduce the number of different scales, and are able to display more elements of the 3D GeoVE. Thus, navigation and orientation tasks may be performed more effectively.

Forty-four participants between the ages 18 and 55 were recruited for the web-based user study, conducted anonymously. The participants had mixed experience with navigation systems and 3D GeoVEs. The study was organized as follows. In a sequence of questions, the participants had to choose between two different pictures showing the same route but with different visualization techniques (e.g., a 2D, 3D, PP, or DP). The

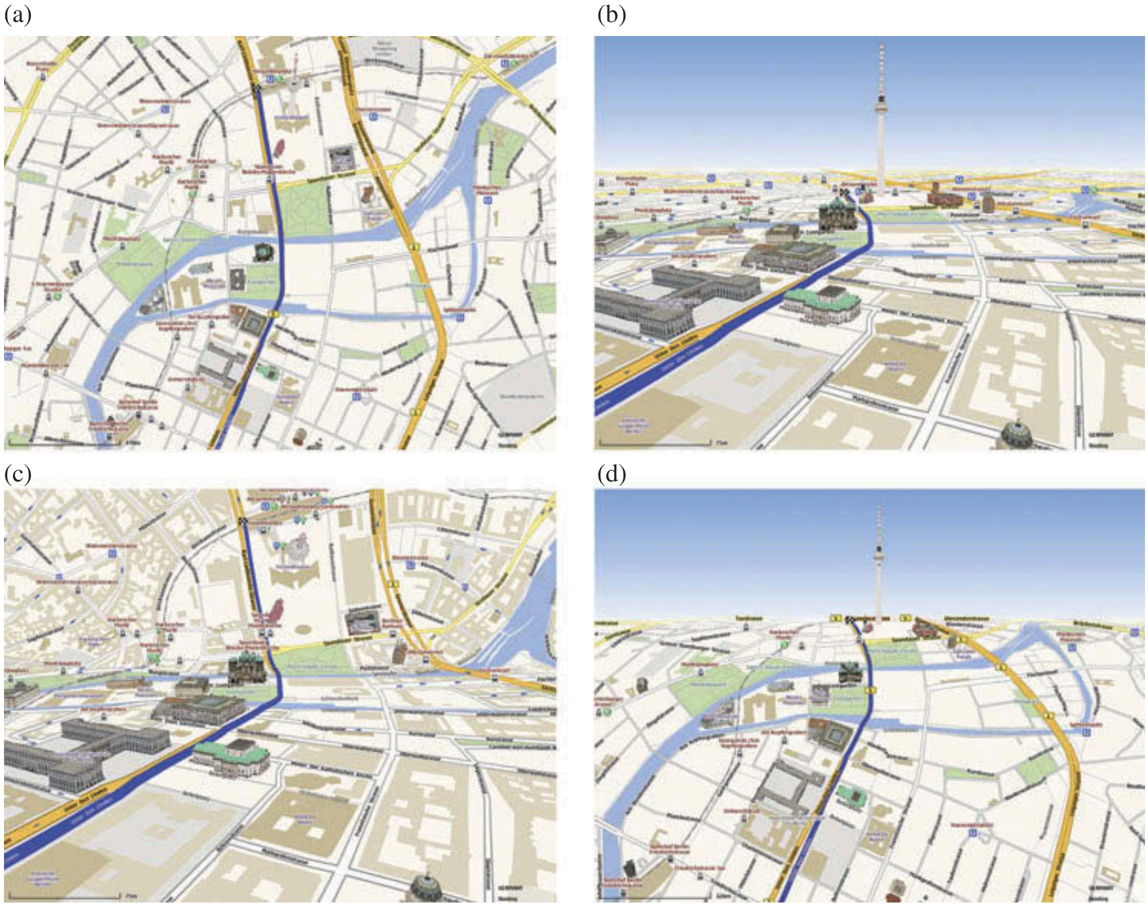

Figure 8. (a) Example of a 2D perspective (2D). (b) Example of a 3D perspective (3D). (c) Example of a degressive perspective (DP). (d) Example of a progressive perspective (PP).

participants' task was to imagine navigating along a highlighted route with the help of a static image from a mobile navigation device. Ten routes of different complexities were prepared that partially contained landmarks. For each route, the four visualization configurations were generated. During the study, 26 image pairs were presented to the participants. Each pair depicted the same route using two different perspectives. Participants were asked whether they favored one of the two visualization techniques or whether they favored one technique over another.

The results of this study are summarized in Table 1, which shows that 80.7% of the participants favored the orthographic perspective over a central perspective. This is reasonable, since a 2D map is an established medium for navigation. Furthermore, 76.1% preferred the DP over a central perspective. This indicates a form of acceptance of MPVs for navigation tasks. With the presented technique, it becomes possible to combine a PP for a low viewing angle with an orthographic perspective for large viewing angles and thus provide the benefits of both visualization techniques in one navigation system.

4.2. Limitations

One main drawback of the 3D panorama technique is the 'unusual depiction' of a 3D GeoVE because of global deformations. A user's lack of familiarity with this kind of

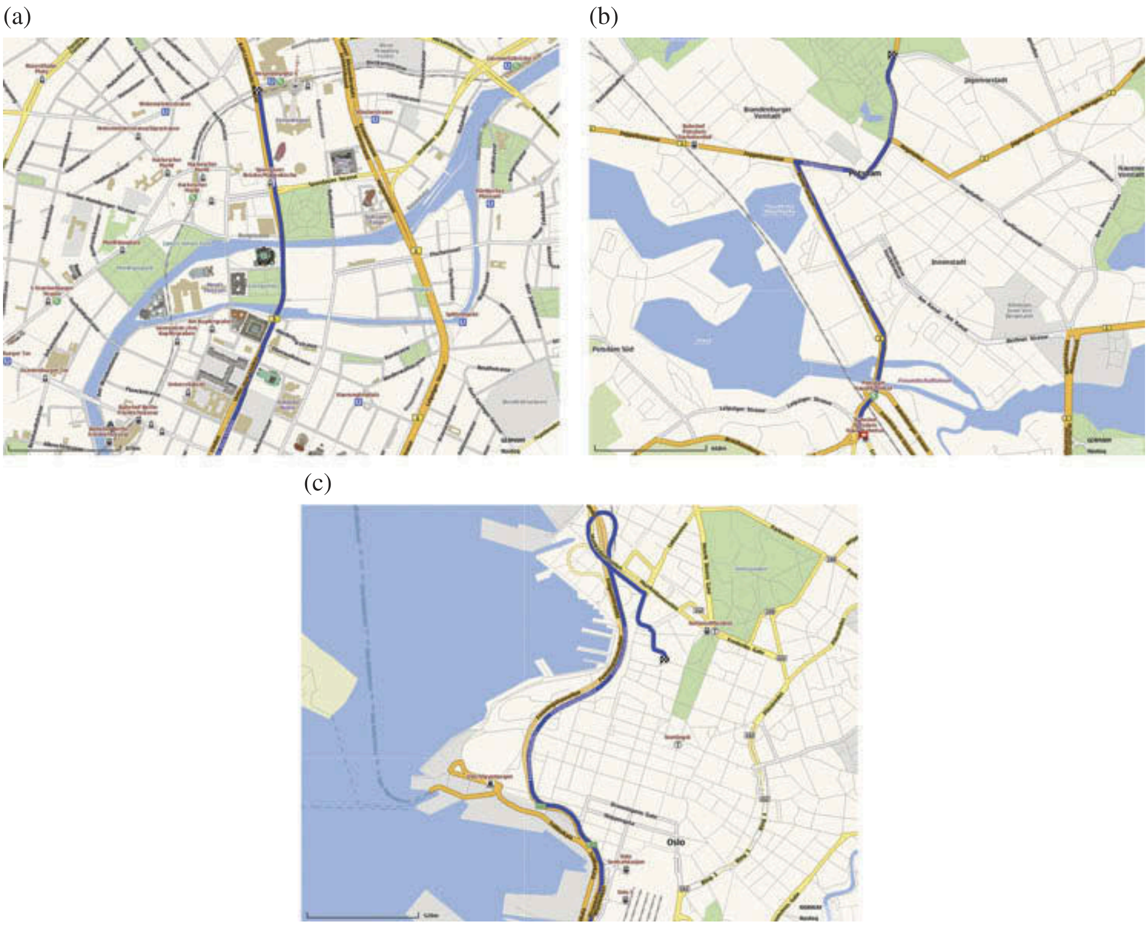

Figure 9. (a) Example of a simple route. (b) Example of a moderate route. (c) Example of a complex route.

Table 1. Results for the user test.

Setup	1st Choice (%)	2nd Choice (%)	No Choice (%)
3D vs. 2D	19	80	1
DP vs. 3D	76	20	4
DP vs. 2D	31	57	12
PP vs. 3D	31	59	10
PP vs. 2D	8	88	4

projection can lead to several side effects such as a misinterpretation of the panorama as a mountainous region in static images or simulator sickness in fully immersive environments (e.g., CAVE systems). To cope with misinterpretations, 3D panoramas can be subdivided into distinct view-angle zones, uniformly depicted with a distinct view angle (Jobst and Döllner 2008b). To emphasize this effect, the curved transition zones are minimized, and an abstracted, cartographic visualization is applied (Jobst and Döllner 2008a, Pasewaldt *et al*. 2012). From our experience, simulator sickness is a direct result of the missing horizon, which often serves as a point of reference for the human eye. Replacing the horizon with parts of the virtual 3D model requires the human to find an alternative focus point. However, the 3D panorama is not intended for virtual reality simulations but for analytic and exploratory information display. We observed in our tests that this effect was reduced after a short learning phase and only occurred during fast rotations. In many applications, for example, in car navigation systems, this effect is less relevant, as those fast rotations do not occur.

To minimize and to cope with the effects of the unfamiliar perspective, suitable configurations for 3D panoramas and their cartographic visualization should be identified. In their current form, the 3D panoramas provide a technical and conceptual basis for designing a task- and use-case-specific 3D visualization to communicate spatial data. According to related work and existing user studies, the proposed configuration of 3D panoramas for navigation and exploration tasks seems to be reasonable, but it requires further validation.

5. Conclusions

The visualization of spatial information has a long tradition of developing effective presentations that frequently include variations of standard projections, such as those found in panorama maps. In computer graphics and visualization, however, the issue of using specialized or complex projections has not been investigated to a large degree. One possible rationale for this might be that the real-time 3D rendering technology exclusively provided perspective and orthogonal single-view projections; there have not been any real-time enabled alternatives. Because of the progress in GPU technology, however, the situation has fundamentally changed; MPVs can be implemented now as part of real-time 3D applications and systems using shader programs.

In our work, we have investigated and developed a real-time enabled multi-perspective 3D panorama visualization technique that offers a high degree of configuration to be applicable to general and generic fields of application in visualizing 3D GeoVEs and general 3D scenes. The key idea behind the 3D panorama is to provide a seamless integrated focus + context view of 3D GeoVEs together with adaptive cartographic rendering techniques. 3D panoramas, in general, allow for tackling a number of problems in visualizing 3D models by 2D output media: occlusion, screen-space utilization, perspective distortion, and visual clutter. The abstraction of the 3D space is enhanced by complementary techniques for cartographic, non-photorealistic visualization.

The panoramas do not pretend to be a general replacement for perspective views; they can be considered as specialized geospatial visualization tools, which need to be customized and adapted for specific applications such as navigation systems, city information systems, control and monitoring applications, or analysis and simulation systems.

3D panoramas appear to be a promising approach for 3D map-oriented visualizations (e.g., city maps, trade fair premises, routing maps), especially if 3D panoramas are combined with a cartographic visualization that supports the generalization and abstraction of 3D model contents. Most importantly, 3D panoramas can be optimally applied to small displays found in smartphones and tablets, whose display space is a scarce resource ('every pixel counts'). By replacing the horizon with parts of the 3D GeoVE as well as reducing perspective distortion and visual clutter, information density is increased, and the display space is used more efficiently.

In the future, we will investigate how to take advantage of pregenerated generalized 3D spatial models to synthesize 3D panoramas. Generalized variants of complex 3D spatial models contribute to reducing the information load and can be used according to a relevance map (e.g., corresponding to a navigation route or city tour). Here we must explore how to set up a real-time enabled 3D rendering technique that seamlessly combines generalized model components while exploring how to ensure time-coherent visual representations.

Another field of research includes cartographic 3D rendering techniques. Here, the key challenge is to find a coherent set of NPR algorithms that are specific to the frequently occurring types of geospatial objects. Most prominently, topologically complex streets and infrastructure networks and elements such as crossings, tunnels, and bridges still demand more precisely abstracting depictions.

We will also further explore how to port the implementations of panorama techniques to a service-based visualization environment. The overall goal is to discover how to restructure the implementations for scalable server-side and client-side applications in terms of model complexity and number of users. In this regard, we also plan to fit the approach into the ongoing web view service activities of the 3D information management group of the OGC.

Acknowledgements

The authors thank the anonymous reviewers for their valuable comments. This work was funded by the Federal Ministry of Education and Research (BMBF), Germany, within the InnoProfile Transfer research group '4DnD-Vis' (www.4dndvis.de), and the Potsdam Research Cluster for Georisk Analysis, Environmental Change, and Sustainability (PROGRESS), and the Research School on 'Service-Oriented Systems Engineering' of the Hasso Plattner Institute.

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